Library, L. M. A. L.

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 771

GROUND EFFECT ON THE TAKE-OFF AND LANDING OF AIRPLANES

By Maurice Le Sueur

La Science Aérienne
Vol. III, No. 1, January-February 1934

Washington
July 1935

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 771

GROUND EFFECT ON THE TAKE-OFF AND LANDING OF AIRPLANES*

By Maurice Le Sueur

INTRODUCTION

The French Society for Air Navigation has asked me to write a report on the much-discussed subject: "Interference Effect of the Ground on Airplanes."

Theory and practice have always been in agreement with the concept that the flight characteristics of a glider or airplane were distinctly different when the airplane flew some 30 feet above or when it flew quite close to the ground.

Every boy of the "aeronautical generation" has built carefully weighted paper airplanes which, after a quite regular gliding descent, seemed to undergo when near the ground an effect great enough to make them start leveling off as if mother earth wanted to help our machines to fight against the resistance of the air.

Observations on airplanes in free flight have enabled us to observe certain systematic phenomena such as: the greater facility of low-wing airplanes for taking off; the impossibility of certain heavily loaded airplanes to gain altitude; the prolonged gliding power of low-wing airplanes at landing, etc.

Notwithstanding the relative consensus of the observations and despite the acquiescence of the principle of the results with theory, much that is erroneous has been published and disseminated as to the causes of these phenomena.

---

*"L'influence du voisinage du sol sur l'envol et l'atterrissage des avions." La Science Aérienne, January-February 1934, pp. 60-93.

Has it not been said that the wing compressed, between it and the ground, an air cushion which increased its maximum lift? Certain ones, pressed too closely for an explanation, even hastened to add that the ground effect increased the drag.

To disprove once for all these misleading doctrines, permit me to state that all experiments are in accord with the theory for showing that the ground interference, rather than raising the drag, actually lowers it, always supposing the lift to be equal, and in quite noticeable proportions. As to the maximum lift, there is no theory which attests to its increase; in fact, divers experiments in accord with certain theories appear to indicate occasionally a decrease.

In support of this theory I shall quote the results of a number of reports, and incidentally express my appreciation to the technicians and engineers who have aided me in this work: Dr. Ackeret, Zurich; W. Margoulis, Mr. Wood, and Professor Alexander Klemin, of the Guggenheim Foundation; Mr. Johnston, Assistant Editor of Aviation; Mr. Courteilles, of the Central Library; Mr. Fournier, of the S.T.Aé.; and Mr. Toussaint, Chief of the Saint-Cyr Aerotechnical Institute, whose report, published in 1922 (reference 9), contains a lucid and very detailed study of ground interference.

I shall take up the four phases of the problem in the following order:

1) The theories on interference effect;
2) The various experimental methods used to record the phenomenon:
    a) In the wind tunnel;
    b) In free flight.
3) The results of the different investigations which upon analysis reveal a more or less satisfactory mutual agreement between themselves and with the theory;
4) The consequences of the phenomenon on the airplane:
    a) At take-off ;
    b) Immediately after actual take-off ;
    c) At landing.

In the last part I shall not fail to touch upon the subject which so often lends this question practical reasons for controversy: the comparison of high wing and low wing, and the drawbacks of each due to their unlike interference with the ground.

I. THEORIES ON INTERFERENCE EFFECT

To begin with, it is obvious that the "introduction of equations," if I may say so, in this problem is difficult on account of the fundamental discrepancies between the two elements of interference.

The fact that the airplane moves while the ground does not, constitutes no insurmountable difficulty; the laws of flow know how to allow for these special conditions.

The wing of finite span represents a much more complicated case because of the superposition of ground-interference effects and finite-span effects.

It is certain that, to be systematic, the theoretical study and the experiments should first attack the problem of ground effect on an infinite wing, perhaps in line with the experiments made at Saint-Cyr by Mr. Girerd, a pupil of Mr. Toussaint, for his thesis - experiments which convey the determination of the polars of each wing of a biplane with systematic change in the three parameters of wing gap, stagger, and decalage, and which bring out phenomena of greatest importance, especially with very small wing gap.

However, our study is concerned with the general study of the biplane.

One of the artifices in fact which permits posing the problem consists in assuming that the real wing visualized is not influenced by the ground but by a virtual wing which is its symmetrical image with respect to the ground, and to admit that for this simple reason of symmetry the speeds resulting from the reciprocal influence of wing and its image are contained in the plane of the ground.

Accordingly one may deduct this ground which intercepts no circulation, and the interference of the real by the virtual wing is then computed by Prandtl's method, which allows for the induced drag due to the tip vortices of the image and of the speed change produced by the "bound" vortex of the image.

With this theory of Prandtl, Betz expresses the variations in incidence i, and the change in C_x (supposing that C_z is equal) at:

$$\begin{cases} \Delta i = - \sigma \dfrac{C_z S}{\pi L^2} \text{ (in radians)} \\ \Delta C_x = - \sigma \dfrac{C_z^2 S}{\pi L^2} \end{cases}$$

wherein σ is the coefficient of induction,

$\frac{L^2}{S}$, the aspect ratio

When reconciling these formulas with identical terms expressing the induced incidence and the induced drag, it is readily seen that the ground effect is identical with that of an increase in aspect ratio.

All this happens as if the wing had a virtual aspect ratio λ' which increases as one approaches the ground and which is tied to the real aspect ratio λ through the relation

$$\lambda' = \frac{\lambda}{1 - \sigma}$$

so that the formulas for transposing the angles and the C_x may be expressed with

$$\begin{cases} i' = i + \dfrac{C_z}{\pi} \left(\dfrac{1}{\lambda'} - \dfrac{1}{\lambda}\right) \text{ (in radians)} \\ C_x' = C_x + \dfrac{C_z^2}{\pi} \left(\dfrac{1}{\lambda'} - \dfrac{1}{\lambda}\right) \end{cases}$$

Many theoretical or experimental values have been given for coefficient σ. One may admit that it is a function of gap/span ratio h/L (h being then twice the height of the wing above the ground).

Prandtl gives two interpolation formulas for σ as hyperbolic functions of h/L:

$$\sigma = \frac{1}{1 + 5.3\ h/L} \qquad \text{for} \quad \frac{1}{15} < \frac{h}{L} < \frac{1}{4}$$

and

$$\sigma = \frac{1 - 0.66\ h/L}{1.05 + 3.7\ h/L} \qquad \text{for} \quad \frac{1}{15} < \frac{h}{L} < \frac{1}{2}$$

These are the formulas chosen by Toussaint in the previously cited report for comparison with his experimental values for the coefficient in different cases of monoplanes or biplanes with ground effect (fig. 1).

It is noted that these two expressions in hyperbolic form differ very little from each other in the 1/5 to 1/4 zone. On the other hand, the first, aside from being more simple, is also more suitable for extrapolating above

$$\frac{h}{L} = \frac{1}{4}.$$

(In fact, the second gives $\sigma = 0$ for $\frac{h}{L} = 1.5$, which is at variance with the majority of experiments.)

However, as this analysis is to be of a general nature, we shall not attempt a discussion of this theory by Prandtl as announced in 1921 by Wieselsberger (reference 5), nor compare it with other theories established since then.

Quite to the contrary, we shall admit Wieselsberger's formula as transposition method (with, for example, the first formula for σ) and we attribute the experimental data pointed out in our report very objectively to these theoretical data.

This is all the more justified as the greater percentage of experimenters have effectively used this formula as basis as well as having been accepted by nearly every one of the authors quoted.

Nevertheless, we wish to point out, in passing, the other theoretical studies which have been undertaken since on this problem and which result in formulas or results which are more or less at variance with the former.

There is an analysis by Rosenhead of the lift on a flat plane between parallel walls (reference 18) - an analysis based upon a method of conformal transformation whose results are obtained as functions of Weierstrass and theta functions, with numerical applications for different approximations, and which the author compares with Glauert's values.

There is further a study by Müller (reference 19) applying to two symmetrical airfoils visualized in the reflection method, the conformal transformation of Ferrari which, in consequence, is applied to two equal circles and yields a transformation of the type of

$$\xi = \zeta + \frac{P^2}{\zeta + \zeta_0} + \frac{P^2}{\zeta + \zeta_0'}$$

ζ_0 and ζ_0' being conjugated complex numbers and P a real positive inferior number of the radius of the circle.

The choice of ζ_0 and ζ_0' affords thin profiles obtained through the sum of three vectors. It is a generalization of von Mises' method applied to symmetrical airfoils.

The author points out that the results obtained with this method are not in accord with experience because they lead to a decrease in lift, whereas experience indicated an increase due to the fact that the friction against the ground in the vicinity of the wing tends to slow up the flow on the top camber, which promotes circulation.

Another report along the same lines is that by Pistolesi (reference 24), in which the author applies his biplane theory to the reflection method.

Treating first the case of infinite span, he finds that the circulation increases with the angle of incidence up to a certain value of this incidence, beyond which a reversal occurs. This angle for which the influence changes signs is, moreover, not unaffected by ratio h/L but varies with it. Besides, the growth of circulation does not necessarily entail a rise in lift, for it must allow for the horizontal speed. The C_z value in function of C_{z_0} of the isolated wing is:

$$\frac{C_z}{C_{z_0}} \doteq \frac{1 - K\left(\frac{l}{4h}\right)^2}{\left[1 - K\,\frac{l}{4h}\left(\frac{l}{4h} - i\right)\right]^2}$$

The rise up to the value of the incidence is:

$$i = \frac{l}{8h}$$

This formula is to be reconciled with the approximated lift given by Roy in his "Aerodynamique" (edition 1928, page 66):

$$P_1 = - \rho \Gamma \left(V_0 + \frac{\Gamma}{4\pi h}\right)$$

The author then passes to the limited span L, computes the mean circulation, and finds that ratio C_z/C_{z_0} is a fraction of the relative distance h/l, of the incidence i, and also of the aspect ratio L/l.

Figure 2 shows the C_z/C_{z_0} curves as function of i for an aspect ratio 5 and for $h/l = 1$ and $h/l = 0.75$. The proximity of ground is seen to raise the lift at small i and to reduce it at high i; conclusions which, as we shall see, agree with the experimental results.

Lastly, we cite a Japanese report by Tomotika, Nagamija, and Takenouti (reference 23), entitled: "The Lift on a Flat Plate Placed Near a Plane Wall, with Special Reference to the Effect of the Ground upon the Lift of a Monoplane Airfoil."

Having posed the problem of perfect fluid, the writers start by defining the function of the complex velocity by conformal transformation; then they compute the lift component with Blasius' formulas, one being zero and the other fairly confirming the lift equation without interference for the case of a wall at infinity. The authors then give some numerical application.

Figure 3 gives for angles of attack varying between 4° 30' and 36° the algebraic percentage of lift increase versus the relative distance of the wall.

Their final result is identical with that of Pistolesi:

At low incidence the lift increases when the distance from the ground decreases;

At high incidence, however, the lift decreases concurrently with the distance of the ground.

For low incidences, more or less, this law is not at variance with Weiselsberger - no more than with wind-tunnel and free-flight tests made in England, the United States, Germany, and France.

II. EXPERIMENTAL MEANS FOR RECORDING GROUND INTERFERENCE

These were twofold: first on small-scale models in the wind tunnel or on the aerodynamic carriage; subsequently in free-flight tests while recording the characteristics at different attitudes of flight near the ground, at take-off and landing.

A. Tests with Scale Models

Not wishing to go back as far as Betz' experiments in 1912 (reference 1) (which, while revealing negligible interference values, were quite inaccurate), we have found an interesting report by Cowley and Lock, entitled "Cushioning Effect on Airplanes Close to the Ground" (reference 3). This study was based on tests made in England in July 1920, in the 4-foot No. 1 wind tunnel at 13 m/s (40 ft./sec.) wind speed, for a R.A.F. 15 biplane of no stagger, in connection with the "Tarrant" triplane.

The ground was represented in the one case (i.e., stationary flat-plate method) by a vertical sheet of tin 4 feet high, 3 feet long; in the other case, that is, with the reflection method, a duplicate model was made with wings which, except for a slight modification in the under surface, were of R.A.F. 15 section. This model was supported in the reflected position upon a turntable in the floor of the tunnel.

Measurements were made of the lift, drag, and pitching moment for angles of attack ranging from -6° to 14°, and for ground distances of 37 mm (1-1/2 in.) and 68 mm (2-3/4 in.), which is equivalent to $h/L = 0.167$ and 0.306.

At about the same time the Massachusetts Institute of Technology also made some similar tests in the 4-foot tunnel, at wind speeds of 30 miles per hour except in two cases, where it was increased to 40 and 45 miles per hour. These tests, reported by Arthur E. Raymond (reference 6), were made on three 3- by 18-inch models: a Martin No. 2, an R.A.F. 15 special, and a U.S.A. 27. These experiments were also made by the flat-plate method (3-ply birch 3/8 inch thick, 4 feet high, 3 feet wide, with leading edge chamfered on the sideway from the model), and by reflection method.

In both cases the tests were run at a fixed angle of incidence, for different ground distances varying from 1/4 chord to 2 times chord.

The same experimental method was used in 1921 in Germany to check Wieselsberger's formula and subsequently, Munk's method for biplanes, deduced from the Prandtl theory. These experiments (reference 5) were made on a monoplane model of 124 cm (48.82 in.) span, aspect ratio 9.

Some years later Toussaint made a series of systematic experiments in the $6\frac{1}{2}$-foot No. 1 wind tunnel at Saint-Cyr (reference 9). The ground was represented by a sheet of aluminum 4 mm (0.157 in.) thick, 1.60 m (5.24 ft.) long. The recordings were effected on a wire balance, the wires passing over grooves in the sheet above. The wind speed was 32 to 33 m/s (105 to 108.3 ft./sec.) in the open- and in the closed-throat wind tunnel. The models were a Lioré C.C. 133a wing, a Fokker S.C. 106a wing, a Fokker S.C. 106a+b biplane wing, as well as two Breguet 14A2 airplane models of 1/10 and 1/20 scale. He measured both lift and drag, C_z and C_x, in stages of 3° each, from -9 to +15, and for three distances: 0.530, 0.438, and 0.240 m (1.74, 1.44, and 0.787 ft.). The interference factor σ in each case was deduced from the test data with Betz' formula, and the obtained figures checked against the theoretical figures of Prandtl's formula. We shall refer to the results again later on.

From among other wind-tunnel tests we wish to mention those made in the Eiffel tunnel, whose equipment has recently been described in this periodical. In the tunnel where the model is attached to the balance by an upper surface support, a platform representing the ground may be shifted and fixed at varying heights.

Among the tests in this tunnel at 25 m/s (82 ft./sec.) wind speed, we cite from memory the tests on a Caudron R 220 model, for which the distance of the platform was successively spaced at 0, 100, 200, 300, 400, and 500 mm (3.94, 7.87, 11.81, 15.75, and 19.69 in.).

Unfortunately, as far as the angles are concerned, the experiment is far from being systematic enough: one, 0° in the range of $C_{x_{min}}$ and the other, 12° in the zone of $C_{z_{max}}$.

Such incomplete tests afford no accurate information.

The experiments of the Wibault-Penhöet company, on the other hand, are much more complete, and particularly on:

1. <u>Airfoil 172</u> - mean thickness 14.23; under surface with double camber; theoretical C_{mo} = 4.125; aspect ratio 5; dimensions, 1 m by 0.20 m (3.28 by 0.656 ft.)

Tests with ground distances of 100, 200, and 300 mm (3.94, 7.87, and 11.81 in.) compared with case of ground at infinity (i.e., no plate). Recording of lift, drag, and pitching moment for angles 0°, 6°, 12°, 15°, and 18°.

2. <u>Low-wing monoplane 313, airfoil 209</u> (complete 1/10-scale model) - aspect ratio 7.8; dimensions, 180 by 1135 mm (7.09 by 44.7 in.).

Tests with ground distances at 10, 110, and 210 mm (0.394, 4.33, and 8.27 in.) from base of wheels, compared with ground at infinity. Lift and drag for angles 3°, 6°, 9°, 12°, and 15°.

3. <u>Low-wing monoplane 280, airfoil 125</u> (complete 1/20-scale model) - dimensions, 202 by 1130 mm (7.95 by 44.5 in.); effective aspect ratio 6.84; real aspect ratio 7.85; ground distances of 5, 105, and 205 mm (0.2, 4.13, and 8.07 in.), compared with ground at infinity. Lift and drag for angles of 3°, 3.6°, 12°, and 15°.

4. <u>Low-wing monoplane 287, airfoil 215</u> (complete 1/20 scale model); dimensions: 210 by 1300 mm (8.27 by 51.2 in.); total aspect ratio, 8.4. Ground distances of 12, 112, and 212 mm (0.472, 4.41, and 8.35 in.), comparison with ground at infinity; lift, drag, and pitching moment for angles of 0, 6, 12, and 18°.

Note: In the case of the 18° angle, the 12 mm (0.472 in.) distance could no longer be realized because of the tail skid. In this particular case the plate was dropped 49 mm (1.93 in.) instead of 12 mm (0.472 in.).

5. <u>Low-wing seaplane 240</u>.- Only one interference test was made, corresponding to skimming over the water, and for angles of 6°, 0.6°, 12°, and 18°.

Lastly, we shall mention the tests reported by Dätwyler (reference 22) in his Doctor's thesis. These comprised:

1) flat-plate method tests in the small Göttingen wind tunnel on a rectangular wing of symmetrical profile, 200 by 800 mm (7.87 by 31.5 in.), fitted with vertical elliptical end plates of 250 by 300 mm (9.8 by 11.81 in.).

2) reflection-method tests in the Zurich wind tunnel (two symmetrical wings of 100 by 470 mm (3.94 by 18.5 in.)).

The results obtained for very short distances are, as we shall presently see, extremely interesting.

Tests on aerodynamic carriage.- From among these tests we shall cite those described by E. Tönnies, in a report which may be considered as one of the most complete studies on this subject (reference 21).

Lacking a wind tunnel, the Technical Institute of Hanover, designed and perfected a small carriage actuated by a falling weight over a straight rail 72 feet long, at a speed of 6.50 m/s (21.33 ft./sec.). On this carriage was mounted a wind-tunnel balance supporting the tested model, a Göttingen wing section 365, suspended from a system of levers permitting its height changes above the ground. A stylus recorded the horizontal and vertical displacements of the airfoil on paper mounted on a cylinder.

During a time interval of 0.77 second, which corresponds to a run of 5 m (16.4 ft.), during which the motion was accelerated, the accelerations being recorded on a constant speed cylinder in function of the path followed by an electromagnetic tuning fork fitted with a stylus. This record of the loads in each point of the trajectory permits the calculation of the lift coefficient.

The authors point out that, since the acceleration was not constant during these 5 meters, the graphs disclose a certain lag due to friction and air resistance.

The measurements have afforded a table which for different angles of attack and different wing distances give the recorded acceleration, then the corrected lift, and lastly, the lift coefficient C_z.

The experimenters further confirmed their method by satisfactory comparison (to within 2 or 3 percent) with the lift values recorded in the Göttingen wind tunnel and according to the above-described tests. Analysis of their approximations disclosed during the acceleration period an accuracy of 1/100 second for the time interval - an accuracy of 1/4 mm (0.00984 in.) for the distance covered by the carriage and ±0.035 for the lift coefficient C_z. The accuracy of the angles is given as within 1/4 degree.

B. Full-Scale Experiments

Here the full-scale investigations made in the U.S. in 1927 and related by Elliott G. Reid (reference 12) merit special mentioning.

The experiments were made on a Vought VE-7 biplane, whose aerodynamic characteristics had been previously determined by glide tests and by check tests at approximately 500 feet altitude and several propeller speeds.

The propeller characteristics having been calibrated, the r.p.m. of the propeller recorded in level flight thus became a criterion of the absorbed torque. It sufficed then to effect level flights very close to the ground; that is, to say, at such heights that the lower wing was from 5 to 9 feet above the ground.

The speed and r.p.m. measurements made then from these tests allowed the calculation of the lift and drag characteristics of the airplane in flight subject to ground effect, and the comparison of these data with those determined by the same method beyond the interference zone.

The interesting feature of this method is the principle resorted to to eliminate the necessity of maintaining strictly level flight. Three or four runs were made with different throttle settings, with gain or loss of altitude during 30 seconds, and reading of the revolution counter for the same time interval. The r.p.m. for level flight was then interpolated on a plot of altitude change versus r.p.m.

Other interesting full-scale tests are cited in Tönnies' report (reference 21). The latter, referring to the preceding U.S. investigations, regrets that the authors did not have the advantage of extending their investigations to include the changes in angle of incidence and the deformations of the polar in function of the "ground effect," and he explains the test flights made on a Klemm 26-2a at Hanover.

This time the principle was to record concurrently: the height of the wing above the ground, the speed, and corresponding angle of attack. The records were made with a Zeiss motion-picture camera, timed for one exposure per second. The time of flight (head wind) was staked out by three posts 50 m (164.04 ft.) apart. The camera was mounted sideways facing the pole and 160 m (524.9 ft.) high. The pilot first flew past the poles with his wheels 10 to 20 cm (0.394 to 0.787 in.) from the ground, or at about 1 meter (3.28 ft.) height for the wing while the angle of incidence was recorded. Admittedly, this flight was very delicate and dangerous.

This was followed by flights at 2, 4, 7, 10, 15, and 20 m (6.56, 13.12, 22.97, 32.8, 49.2, and 65.6 ft.) height. The experiments were numerous and followed a set schedule; in fact, several systems of checking were used. Flights were made with head wind, as well as in winter time, in absolutely still air with a thin layer of snow on the ground. The films were projected on paper with millimeter squares, so as to record the three characteristic points of the incidence: lower tip of propeller, low point of the wheels, and tip of tail skid. The report of the films gave the speed and the angle of incidence (within about 10 minutes). The height was read on the photograph of the test scale.

These experiments are remarkably interesting, and we only regret that no similar tests have been made in France.

Incidentally, we would like to make a minor suggestion. The taking of the motion pictures is in two stages: first, the actual photographing and then its projection on the screen. This evidently is a source of error, or of more or less inaccuracy. We would prefer a method in which, for speed measurement, the flown distances recorded with an accuracy of land surveying, are recorded in time rate by instantaneous stops. For the rolling speed on the ground, for instance, equidistant parallel lines at right angle to the path would be formed by small starting balances or trips, on which the passage of the wheels closes - or better yet - interrupts an electric circuit.

For the flight speed an airplane radio with continuous sending could be used, fixed frames being arranged for recording the passage of the airplane in the vertical planes perpendicular to the plane of the trajectory, as well as in the horizontal planes perpendicular to the same plane, which would permit of retracing the flight path in time rate and through it, the speeds.

As to the recording of the rate of rotation of the wheels, we believe that a direct mechanical record would be much more simple than the cinematographic record made from the outside. This is also the opinion voiced by J. G. Lee (reference 16).

With respect to the angle of attack, we think that recording inclinometers would be no less accurate than the motion-picture camera.

III. TEST DATA - THEIR MUTUAL AGREEMENT AND THEIR ACCORD WITH THEORY

In reviewing the results of the different experiments above, on monoplanes as well as on biplanes, in the wind tunnel and in free-flight tests, we can always refer them satisfactorily to Wieselsberger's formula which we translated in variation of aspect ratio:

$$\lambda' = \frac{\lambda}{1 - \sigma}$$

Cowley and Lock's comparison in 1921 (reference 3) for $\frac{h}{L} = 0.167$ and 0.306 shows that there is no accord between the reflection and the flat-plate method, especially for very small distances, and the authors find the discrepancy so great that they openly doubt the method.

Their suspicion includes, in fact, both the reflection and the flat-plate method. With the flat plate they impute the disturbance set up by its leading edge which causes the air flow to deflect upward, and they specify that a displacement of about a degree seemed to bring the curves into fair agreement. Now, in a paper by G. I. Taylor, "Skin Friction on a Flat Surface" (reference 8a) (see also Appendix of reference 3), he states that it requires only 1/8 degree for the angle of deflection due to the deceleration of the air through skin friction on a plate, which is not enough to satisfy us.

By the reflection method the authors raise the element of doubt about the assumption of symmetrical flow about a symmetrical body, and it is a fact that an asymmetrical oscillatory flow with alternating vortices could equally well be used as a basis for computing the interference.

However it may be, we preserve from these experiments the following conclusions given by the authors:

The greatest effect of the ground interference is that upon pitching moment; the smallest effect, upon maximum lift.

The maximum L/D is increased from 10 to 13 in the case of the reflection method, and 10 to 15 for the flat-plate method.

For the plate at 38 mm (1.496 in.), which is equivalent to a wing gap of 76 mm (2.99 in.), i.e., $\frac{h}{L} = \frac{1}{6}$, the experimental values obtained by the flat-plate method are about twice those obtained by the reflection method (that is, for increase in lift and L/D (fig. 4), supposing that the angle of attack is the same).

Lack of time prevents our checking the five tables of these experiments and comparison of the experimental σ with that obtained according to Wieselsberger's multiplane formula, and we only insist on this single or double discrepancy between the results of the two test methods - differences which our own experiments on monoplanes have failed to reveal accurately, as shown elsewhere in the report.

Raymond (reference 6) in his report on the tests in the U.S. gives qualitatively the same discrepancy between the two test methods.

The lift and drag curves versus angles of attack for the U.S.A. 27 wing tested with the ground at 1/2 chord, are more marked by flat-plate than by reflection method, and the results of the two methods again manifest the order of size of single or double (fig. 5).

In our own tests made in the Eiffel wind tunnel, we employed only the reflection method. As they systematically indicated a very much greater influence than Wieselsberger's formula stipulated, and the results have never been published, we shall recount them herewith:

1. Profile 172.- The values for σ_2, σ_4, and σ_6 computed for 100, 200, and 300 distances, or $\frac{h}{L} = 0.2$, 0.4, and 0.6 are tabulated as follows:

100 C_z	100 σ_2	100 σ_4	100 σ_6
40	0.88	0.69	0.54
50	0.85	0.66	0.535
60	0.85	0.655	0.545
70	0.85	0.625	0.53
80	0.85	0.60	0.49
90	0.805	0.535	0.445
100	0.745	0.505	0.415
110	0.705	0.475	0.38
120	0.72	0.49	0.38
Mean experimental value	0.85	0.58	0.47
Theoretical value (Prandtl)	0.48	0.29	0.23

2. <u>Monoplane 313</u>.- For distances of 150, 250, and 350 of the wing from the ground, of $\frac{h}{L} = 0.264$, 0.44, and 0.615, the data are:

$100\ C_z$	$100\ \sigma_{0.264}$	$100\ \sigma_{0.44}$	$100\ \sigma_{0.615}$
90	71.2	34.2	31.8
100	67.2	40.2	25.6
110	63.5	38.3	24.2
120	63.0	38.5	25.6
130	59.4	39.8	26.8
140	53.6	39.4	28.7
150	41.5	33.2	25.1
Average experimental	60	38	27
Theoretical	40	28	23

This time the excess is less pronounced, although it still amounts to 50 percent of the theoretical value for the smallest distance.

3. Monoplane 280.- $\frac{h}{L}$ = 0.15, 0.33, and 0.505. The comparison reveals:

100 C_z	100 $\sigma_{0.15}$	100 $\sigma_{0.33}$	100 $\sigma_{0.505}$
30	96	36	96
40	81	34	54
50	79.5	41.5	41.5
60	75	42	39
70	70.5	41.7	35
80	65.5	40.3	32
90	62.5	38.5	30.5
100	59	38.5	30
110	58	38.2	30
120	60	40	31.5
130	78	52.5	37.5
Mean experimental	71	40	36
Theoretical	55	36	27

Again the experimental figure is higher than the theoretical, but this time it does not exceed 30 percent for the smallest distance. On the other hand, for this smallest distance the polar intersects the other polars for lift values of the order of 30 or 40. As this zone corresponds to -3° incidence, we believe that it might be a question of a symptomatic singularity, of a turbulence, but that point remains to be proved.

4. Monoplane 287.- Wheel distances: 12, 112, and 212 mm; $\frac{h}{L}$ = 0.28, 0.53, and 0.78 (with allowance for height of wing above the wheels).

100 C_z	100 $\sigma_{0.28}$	100 $\sigma_{0.53}$	100 $\sigma_{0.78}$
60	106	84.5	55
70	92.7	72.6	47.4
80	82.7	65	44
90	78.6	59.4	43
100	79.2	61	44.8
110	78.3	59.5	45
120	75.5	58.3	46.1
Average experimental	84	66	47
Average theoretical	39	26	20

Here we find the displacement from single to double, emphasized in the test with isolated wing (fig. 7).

In the face of these results, we can conclude only that, because of a certain suspicion against the flat-plate method, particularly when the plate is, as here, of a certain thickness and, in order to support our suspicion, we had resorted to a number of other tests as unlike as possible and which are not only in accord with the principle of Wieselsberger's formula but also in order of size of the coefficient.

We recall Toussaint's report (reference 9) which verifies the theoretical formula very correctly, as shown in figure 1.

We likewise recall Wieselsberger's report on the Göttingen experiments in 1921 (reference 5). The dimensions and distances were: $L = 1.24$ m (4.07 ft.), $S = 0.1675$ m^2 (1.8 sq.ft.), $h/L = 0.242$.

The corresponding $\sigma = 0.432$, so that $\Delta C_x = -0.0150 C_z^2$. The experimental results verify this formula very correctly and the computed polar is coincident with the measured polar up to lift values of the order of 62.5. Then the theoretical C_z drops suddenly, as observed in the recent theories outlined above (fig. 8).

In conclusion, it may be stated that the interference tests in the tunnel are not at variance with the theory, but that the premise of continuous parallel flow remains to be verified in each particular experimental case by the reflection method and particularly by the flat-plate method.

Passing now to the carriage tests described by Tönnies (reference 21), we find that the different tests on the different models for h/L ranging from 0.1 to 0.5 reveal perfect agreement with Wieselsberger's theory. At high incidence (16-18°) there is not only no increase in lift, supposing equal angle of attack, but rather a decrease which also concurs with the theory (figs. 9, 10, and 11).

Figure 10 gives the lift versus incidence for different h/L, while in figure 11 the carriage test intersects the Göttingen tunnel polar twice.

As to the U.S. tests, described by E. G. Reid (reference 12), they agree very well with the formula, as shown in figures 12, 13, and 14.

Figure 12 gives the curve of r.p.m. versus air speed for 500 feet altitude and the r.p.m. versus air-speed curve of the low-altitude tests.

Figure 13 shows the curves of required thrust horsepower versus air speed, and figure 14, the normal polar curve of the VE-7 airplane, without interference, as determined by glide tests.

This polar has been transposed by the formula for the three σ values corresponding to 5, 7, and 9 feet. Then the experimental polar for flight in proximity of the ground was plotted on this graph for the zone between 5 and 9 feet. Thus the experimental polar remains perfectly within the transposed theoretical polars, which a posteriori justifies the formula of transposition.

Coming to the flight tests described by Tönnies (reference 21) on a Klemm monoplane at heights ranging from 3 to 82 feet above the ground, we readily see on the polar of figure 15 the experimental lift values, i.e., deduced from the measured speed values through the fundamental formula:

$$C_z = \frac{K}{V^2}$$

For $i = 4^\circ$ and $h/L = 0.155$, the lift coefficient of the airplane increases by 10.3 percent (as against 35 percent in the wind tunnel for the wing alone). The author attributes this discrepancy to supplementary disturbances, augmented by the wheels, propeller, body, etc.

In figure 16 we give the flight polar in full lines, and its transposition by calculation for $h/L = 0.1$ in dashed lines. The experimental polar for $h/L = 0.1$ is also shown. The accord is very close.

In the majority of the above tests in the tunnel, as well as in free flight, conditions of materiel have prevented the investigation from being pushed to very low h/L values, whereas Dätwyler's wind-tunnel tests stressed this point in particular.

By flat-plate method (fig. 17) for distances decreasing to 5 mm (0.197 in.), the maximum lift increases 20 percent. (Note the discontinuity toward 8°.)

What role does the end-plate disturbance assume in this discontinuity or is it primarily due to the natural disturbance of the flat plate? Figure 18 gives some pertinent information on this point. Independent of the three vortices clearly outlined aft of the top camber, the photograph reveals the compression set up by the plate under the front of the bottom camber, and whose effect, according to Dätwyler, is to narrow, like a materiel wedge, the distance between ground and wing, which explains the loss of lift with respect to the theoretical lift expected by the author.

Contrariwise, by the reflection method (fig. 19) with wing gap decreasing to 1 mm (0.0397 in.), the maximum lift is doubled; it even exceeds the theoretical figure obtained from the static-pressure calculation. These curves, it will be noted, show no break.

Conclusions: I think we have not yet enough lucid experience to formulate any laws. We only aver that, in the first zone (great distances and small angles) the different experiments of all sorts seem to be in agreement with Wieselsberger's law, which likens the ground interference to a fictitious increase in aspect ratio. The effect in flight corresponds to the phenomenon called "floating" in the United States.

In the second zone - high angles of attack, small distance from the ground - there may be a loss of lift; perhaps it is the effect which is observed in certain test flights - an effect which is called "pancake" in the U.S.

Lastly, for very high angles of attack and successively smaller distances from the ground, it may result in a marked rise in lift. This phenomenon brought to light by Dätwyler's experiments will have little or no significance in practice. We should regret this because this will be the true "cushioning effect", the veritable air cushion which assists the airplane at take-off and shows up its drop at landing.

IV. THE CONSEQUENCES OF THE PHENOMENON OF THE DIFFERENT PHASES OF MOTION ON THE AIRPLANE NEAR THE GROUND

Comparison of High Wings and Low Wings from the Point of View of Ground Effect

Now we shall analyze the consequences of ground effect on the different phases of airplane motion in proximity to the ground, with special reference to take-off, skimming over the ground, and landing.

Take-Off

Supposing equal lift coefficient C_z, the effect of the ground is to so reduce the drag C_x, that is to say, the power required - which varies as $C_x/C_z^{3/2}$ - that the airplane may be considerably finer within than without the zone of ground effect.

In certain cases the power required may be reduced as much as 50 percent, and that at a ground distance of the order of the wing span of the airplane. Under these conditions the ground effect always promotes take-off save in a case, however, of heavily loaded airplanes such as used for long-distance flying, which can only take off with favorable ground effect but which, then, are unable to get away from this littoral zone for the reason that, immediately after take-off, the power required to maintain level flight resumes its normal figure and becomes greater than that necessary when the airplane is just clear of the ground, whence lift in horizontal flight is impossible.

Some typical cases are cited and analyzed by Elliott G. Reid and Thomas Carroll (reference 14). The writers cite in particular the case of such a very heavily loaded airplane, which at that time was under test at their laboratory at Langley Field and which was successfully taken off but could not be forced above an altitude of about 50 feet, where level flight was maintained for approximately 10 miles, at the end of which the pilot succeeded in landing without attempting to make a turn.

The writers further cite the transoceanic airplane "American Legion", piloted by Commander Davis and Lieutenant Wooster, at Langley Field, which, taking off under full-load conditions, left the ground after a run which was even somewhat shorter than had been anticipated, but could not climb beyond 30 to 50 feet. Unfortunately, this time a clump of trees prevented the pilot from continuing in that direction and forced him either to rise or turn. It ended in a loss of altitude followed by a glide - that is, to say, disaster.

The authors also cite, but without giving details, Peltier d'Oisy and Gonin's start for India, their flight for approximately $2\frac{1}{2}$ miles at an altitude of not greater than 30 to 60 feet - after which they were forced to land again, both men fortunately escaping from the airplane, which was entirely demolished as a result.

The authors also give some information concerning Colonel Lindbergh's preparations, which were directed almost entirely toward determination of the take-off, giving less consideration to the phenomenon of ground effect.

It is to be noted, moreover, that the limited ceilings above confirm Reid's experiments, particularly with a conventional VE-7 biplane of 34.4 feet span and whose minimum power required for level flight is about 7 feet above the ground, i.e., equal to about 1/2 the span of the airplane. Thus at an altitude of 500 feet, the power required was 33.5 horsepower, whereas when the airplane descends until its lower wing is approximately 7 feet above the ground, only 23.5 horsepower is required to maintain level flight. This readily explains the lightness felt by the pilot at the point of leaving the ground; the airplane rises more easily than expected, but seems to become heavier while climbing.

Many graphical or analytical methods for take-off, landing, and take-off run have been proposed. Tönnies, in the article already mentioned (reference 21), reverts to Blenk's formulas (Z.F.M., 1927, p. 25) which, proceeding from the elementary equation of motion on the ground:

$$\frac{P}{g}\frac{dv}{dt} = T - R_x - R_f$$

(with allowance for propeller thrust and coefficient of friction followed by integration), result in a quite complicated formula for take-off and rolling distance. This formula may, however, be simplified by virtue of some conventions on the desired approximation.

Tönnies then compared the rolling distance obtained with this formula with that obtained on different types of parasol, low-wing monoplanes and biplanes. Figure 20 reveals the satisfactory agreement of the comparison.

On an average, the measured rolling distance l_m is about 130 feet greater than the theoretical l_c. Figure 21 shows the ratio of rolling at take-off to power loading versus thrust (in kilograms) for different types of airplanes. A glance at these two figures reveals that, supposing equal wing loading, the low wing has the shorter run.

Flight Immediately after Take-Off

Here the imagination of inventors is offered a vast field. The ground interference reduces the power required for level flight in large proportions, so here is a means of rapid and at the same time economic locomotion: Design an airplane which is always within the ground-interference zone.

At first glance this apparatus is dangerous because the ground is uneven and the altitude called "skimming" permits no freedom of maneuver. But on large-sized aircraft, over water, the question may be attempted. It is not at all unreasonable to conceive of an aerial steamer - part airplane and part hydroplane - able to sustain itself partly in the air and partly on the water, but requiring for aerodynamic lift 50 percent less power than required, say, for the lift at high altitude.

We merely make this suggestion without any further statement.

Landing

Here the problem begins to be interesting. What is the effect of ground interference on landing? Is it beneficial or detrimental? Here we are obliged to say that the interference which favors take-off, impedes landing in restricted territory.

Besides, the landing speed is one of the most imprecise factors in aviation, as proved from the following example. An American, Elliott G. Reid (reference 15), has had the courage to expose the fantastic landing speeds given out by the airplane manufacturers in the United States. With his statistics, delicate to the point of ignoring simple cases of obvious bluff, the author gives in a plot the alleged landing speeds versus wing loading. The points which should aline themselves in a region corresponding to a reasonable lift coefficient resemble, on the contrary, the author says, the familiar charts of "the heavens in June" (figs. 22 and 23). Examination of the two graphs gives conclusive proof of the bluff "ab absurdo".

On the subject of ground interference, the author again displays his good sense by declaring that there is nothing particularly mysterious about the effect of proximity to the ground upon wing characteristics, and that it is simply a reduction of the induced angle of attack accompanied by a decrease of the slope of the lift curve; yet it should not be forgotten that the lift approaches an asymptotic value, which is that which corresponds to high-aspect-ratio airfoils, and that the induced angle - which alone decreases - is, itself, a small part of the geometric angle of attack.

Lack of time prevents further development of the different investigations - in the U.S., for the major part - on the experimental determination of landing speeds of airplanes.

We briefly summarize the article by J. G. Lee (reference 16), who, after voicing his skepticism about the value of wind-tunnel tests, gives two flight-test methods which were most commonly used and which are, according to him, within 5 percent correct.

The first consists of calibrating the air-speed meter by flying over a course at various speeds and then reading the air speed at the moment of landing. Generally, the average of several landings is taken. The second method consists of mounting an electric recording instrument to the wheels. If the landings are correctly made on three points, Lee estimates that the accord between these tests and the wind-tunnel polar is satisfactory.

The first method is employed by Thomas Carroll (reference 13) who, in N.A.C.A. Technical Report No. 249, gives statistics of landing speeds recorded by direct indicator reading with, it appears, an accuracy of 3 percent.

In Kenneth F. Ridley's report, on the other hand, (reference 17), we read - after a slight criticism of Carroll's method - the description of proper procedure.

This consisted of painting the wheels of the airplane in contrasting colors and then photographing the airplane while making 3-point landings (wheels and tail skid at the same height); wind speeds were simultaneously read from an anemometer.

The method of prediction, indicated by the author and illustrated by numerous examples, consists of computing the induced polar by Wieselsberger's formula applied to the normal polar. This is the lift read on this new polar which, included in the lift equation, gives him the predicted landing speed which the author says checks to within 4 km/h (2.49 mi./hr.) of that obtained on 11 different airplanes. This is in close approach, despite the sources of inaccuracies analyzed by him.

To return to our subject, we must conclude that the effect of the interference, by reducing the drag for equivalent lift, is to prolong the flight quite close to the ground. The $C_x/C_z^{3/2}$ curves shown, reveal that the minimum power of the wing may be reduced by 1/4, even 1/3, advantageously, by the ground effect which, when landing on a perfect track, tangentially to the ground, forces the airplane to absorb for a long period the kinetic energy of its motion in order to reach its minimum speed at impact.

Does that mean that, in view of the size of the terrain, the ground interference is inauspicuous at landing? Or does it imply that a low-wing airplane is, under these conditions, inferior to a parasol monoplane? Quite fortunately, no, because the normal landing is not a landing of a theoretical track.

To illustrate: Visualize the comparison of a low-wing commercial monoplane with a monoplane whose wing hangs over the cabin - that is, to say, 5.8 feet higher from the ground. The ground effect is not a prerogative of the low wing; which is only 5.8 feet more subjected to it than is the other. So when the interference changes from 10 to 15, the supplementary "floating" of the low wing relative to the parasol wing may already be limited to 5 × 1.80 m (5.906 ft.) = 29.5 feet.

However, this is not definite because when referring to the analytical study of landing by L. Breguet, (La Science Aérienne, vol. II, no. 3, December 27, 1932), we find that the low wing may, on the contrary, assume the advantage in the last two of the four stages of landing analyzed by the author. In the level-off stage, particularly, the low wing, being finer because more interfered with, has a maneuverability which allows it to run through the range of level-off angles more easily. It only needs an adequate pull-up to reach or even exceed the angle of maximum lift. In flyers' language, the low wing "sets down" better.

Then comes the rolling stage. What matters the maximum decrease in lift? The low wing has no tendency to nose over because its c.g. is low; consequently, it can sustain a more energetic application of the brake. Besides, experience has proved that - supposing equal unit load - the low-wing airplane has as short a landing run as the parasol type. However, the pilot should not find himself surprised by the effect of decreased induced angle due to ground effect.

This is what Tönnies expresses in counseling for better gliding at landing: flying at an angle as small as possible, as long as possible, and not setting down the airplane until the very last moment.

CONCLUSION

In conclusion, we regret that we have not been able to present a more conclusive report on this problem. Our own experiments are still under way and not absolutely certain; our intention was to complete them by a network of facts and figures gathered into one comprehensive report.

We have finished the part dealing with the different theories of interference as well as with the agreement existing between the theory and the major part of the experiments.

In the tests, which are at variance with the theory, we are obliged to detect sources of error or more or less inaccuracy.

Always somewhat skeptical about the time which one may accord to wind-tunnel tests, we prefer full-scale investigations, especially when, as in the preceding case, they are readily obtainable.

The flight tests of Reid, Ridley, and Tönnies are of greatest interest. I hope that we may soon make them in France, and with variations in the methods, if possible.

Thus we shall measure the phenomenon by its effects which, precisely, are of direct interest to the user, i.e., the pilot. The theoretical formulas derived from these tests will be applicable to future predictions with a much greater legitimacy when tests, calculations, and applications have been put in the same dimension, which proceeds from actuality and from doubtful premises.

With the mastery and engineering skill of our pilots, with the accuracy of our test equipment, the science of flight has a right to be counted among the foremostly developed branches of experimental physica.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

REFERENCES

1. Betz, A.: Auftrieb und Widerstand einer Tragfläche in der Nahe einer horizontal Ebene. Z.F.M., No. 12, 1912.

2. Merrill, A. A.: Ground Effect on Wings. The Ace, December 1920.

3. Cowley, W. L., and Lock, C. N. H.: Cushioning Effect on Aeroplanes Close to the Ground. R. & M. No. 754, British A.R.C., 1921.

3a Taylor, G. I.: Skin Friction on a Flat Surface. R. & M. No. 604, British A.C.A., 1919.

4. Zahm, A. F., and Bear, R. M.: Ground Plane Influence on Airplane Wings. Jour. of the Franklin Institute, May 1921, p. 687.

5. Wieselsberger, C.: Wing Resistance Near the Ground. T.M. No. 77, N.A.C.A., 1922.

6. Raymond, Arthur E.: Ground Influence on Aerofoils. T.N. No. 67, N.A.C.A., 1921.

7. Prandtl, L.: Applications of Modern Hydrodynamics to Aeronautics. T.R. No. 116, N.A.C.A., 1924.

8. Prandtl, L.: Induced Drag of Multiplanes. T.N. No. 182, N.A.C.A., 1924.

9. Toussaint, A.: Contribution à l'Etude expérimentale des Lois de similitude en aérodynamique. Thesis presented to the Faculty of Sciences of the University of Paris, 1924.

10. Bonder, J. Sur le mouvement de deux cylindres dans un fluide parfait, avec application à l'aile au voisinage du sol. Bulletin de la Soc. Polytechn. de Varso-vie, IV, I, 1925.

11. Betz, A.: The Lift and Drag of a Wing in Proximity to the Ground. Memo. Report 167, Engineering Division, Army Air Service, 1925.

12. Reid, Elliott G.: A Full-Scale Investigation of Ground Effect. T.R. No. 265, N.A.C.A., 1927.

13. Carroll, Thomas: A Comparison of the Take-Off and Landing Characteristics of a Number of Service Airplanes. T.R. No. 249, N.A.C.A., 1927.

14. Reid, Elliott G., and Carroll, Thomas: Concerning the Take-Off with Heavy load. T.N. No. 258, N.A.C.A., 1927.

15. Reid, Elliott G.: An Analysis of Airplane Landing Speeds. Aviation, July 20, 1929, pp. 192-194.

16. Lee, J. G.: Landing Speed of Airplanes. A.S.M.E. Jour., April-June 1929.

17. Ridley, Kenneth F.: An Investigation of Airplane Landing Speeds. T.N. No. 349, N.A.C.A., 1930.

18. Rosenhead, L.: The Lift on a Flat Plane between Parallel Walls. Proc. Roy. Soc., London, vol. 132, no. A 819, July 2, 1931, pp. 127-152.

19. Muller: Abbildung theoretische Grundlagen für das Problem des Tragflügels in Erbodennähe. Z.F.M. t II, fasc. 3, June 1931.

20. Tani: On the Effect of the Ground upon the Lift of a Monoplane Wing (in Japanese). Jour. Aeronautical Research Institute, Tokyo Imperial Univ., No. 96, 1932, pp. 684-689.

21. Tonnies, E.: Effect of the Ground on an Airplane Flying Close to It. T.M. No. 674, N.A.C.A., 1932.

22. Dätwyler, G.: Thèse de Doctorat.

23. Tomotika, Susumu, Nagamiya, Takeo, and Takenouti, Yositada: The Lift on a Flat Plate Placed Near a Plane Wall, with Special Reference to the Effect of the Ground upon the Lift of a Monoplane Aerofoil. Report No. 97, Aeronautical Research Institute, Tokyo Imperial Univ., vol. 8, no. 1, August 1933.

24. Pistolesi, E.: Il problema dell' ala in vicinanza del suolo. Pub. by the Royal School of Engineering, Pisa, nos. 218-219, May 1933; L'Aerotecnica, vol. 13, no. 4, April 1933, pp. 351-360-501-502.

APPENDIX

Cowley and Lock*

Cushioning Effect on Airplanes Close to the Ground

Biplane Gap = chord No stagger
Airfoil R.A.F. 15 (Area: 2.3 by 18 inches)

	Table I Biplane alone			Table II Reflection, gap $5\frac{1}{2}$ inches			Table III Reflection, gap 3 inches		
i	100 C_z	100 C_x	100 C_m	100 C_z	100 C_x	100 C_m	100 C_z	100 C_x	100 C_m
-6	-34.2	7.4	9.84	-36.8	7.7	11.92	-46.0	9.2	13.9
-4	-20.6	4.6	9.74	-22.8	4.84	9.84	-28.6	5.46	11.02
-2	-7.6	3.4	8.26	-8.0	3.44	8.2	-11.6	3.68	9.68
-1	- .4	3.1	7.58	- .02	3.08	7.64	-2.8	3.2	8.48
0	6.4	2.96	6.82	-7.4	2.88	6.82	6.2	2.96	7.28
1	14.8	2.96	6.16	19.2	2.76	5.2	17.4	2.88	5.44
2	22.2	3.04	5.36	26.8	3.04	4.36	28.4	3.0	4.12
3	30.8	3.52	4.7	36.0	3.38	2.06	37.4	3.34	2.72
4	38.4	3.92	3.26	42.8	3.7	1.06	46.2	3.72	1.1
6	52.0	4.98	1.6	56.4	4.64	- .76	60.8	4.76	-2.76
8	64.6	6.36	- .3	70.0	6.12	-3.84	71.8	6.0	-6.14
10	78.6	8.0	-3.36	81.4	7.9	-9.1	85.6	7.94	-11.22
12	90.0	10.9	-5.72	92.8	10.56	-11.32	96.0	11.2	-16.36
14	92.8	14.5	-9.26	93.6	17.4	23.2	94.6	18.0	-22.14

*See reference 3.

Plate at 2-3/4 in. distance				Plate at 1-1/2 in. distance		
i	100 C_z	100 C_x	100 C_m	100 C_z	100 C_x	100 C_m
-6	-37.2	7.7	10.0	-36.4	7.54	11.86
-4	-22.4	4.66	8.22	-19.2	4.5	10.08
-2	-8.4	3.36	6.82	-3.6	3.3	8.0
-1	- .6	3.08	5.44	5.6	2.96	6.5
0	7.2	2.92	4.68	15.6	2.72	5.04
1	16.6	2.84	3.12	24.8	2.56	3.56
2	25.8	2.92	2.2	33.6	2.66	1.56
3	34.6	3.24	1.04	41.6	2.9	.06
4	42.2	3.56	- .26	49.6	3.3	-1.14
6	55.6	4.56	-2.88	63.6	4.34	-4.72
8	68.8	5.94	-5.66	77.0	5.66	-8.96
10	82.6	7.96	-9.9	87.0	7.9	-12.88
12	91.0	11.0	-13.88	95.6	11.32	-17.9
14	91.4	17.4	-19.72	94.2	17.62	-24.8

Wing gap and plate distance are measured starting from lower wings and for 0° incidence.

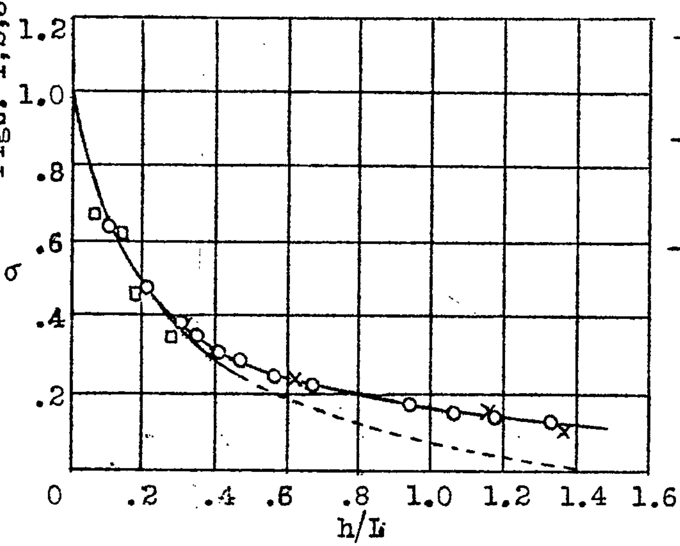


Figure 1.- Change of coefficient of interference in biplanes. (Span = wings of biplane).

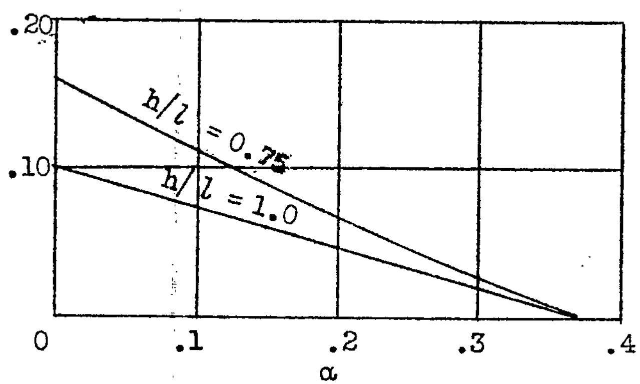


Figure 2.- Pistolesi's biplane theory applied to the reflection method. (reference 24)

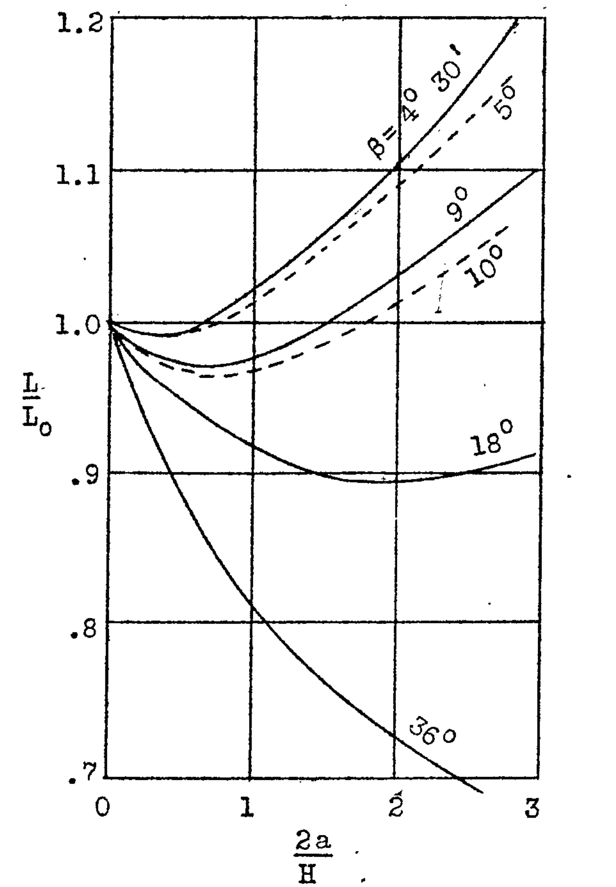


Figure 3.- Effect of ground proximity H on the lift of a plate L. (Tomotikie, reference 23)

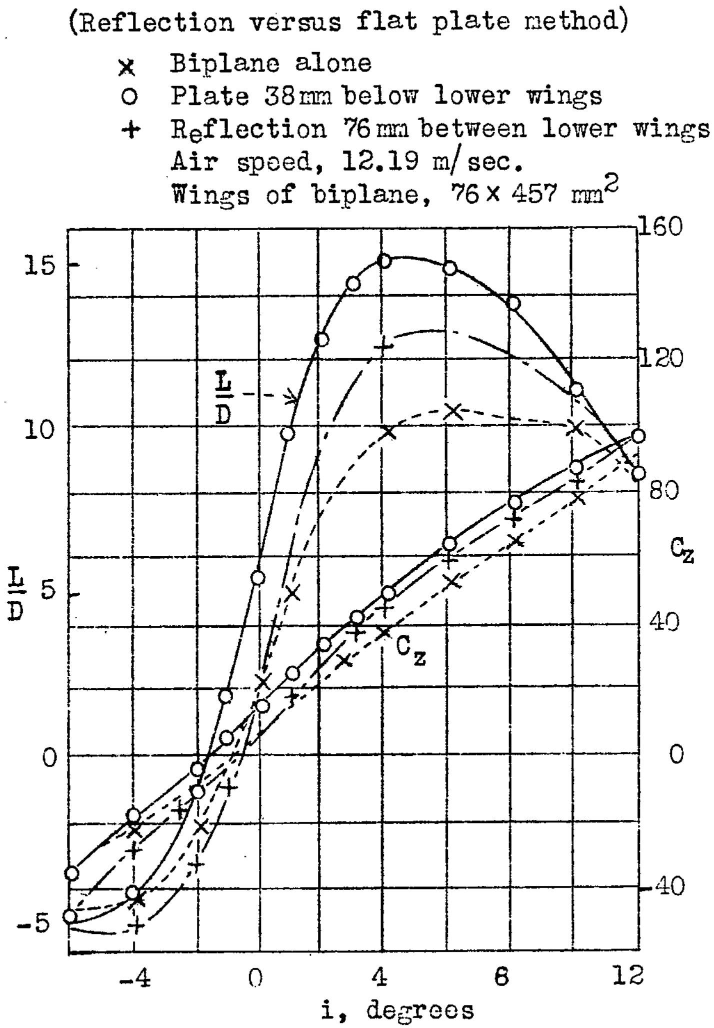


Figure 4.- Cushioning effect on airplanes in proximity of the ground.

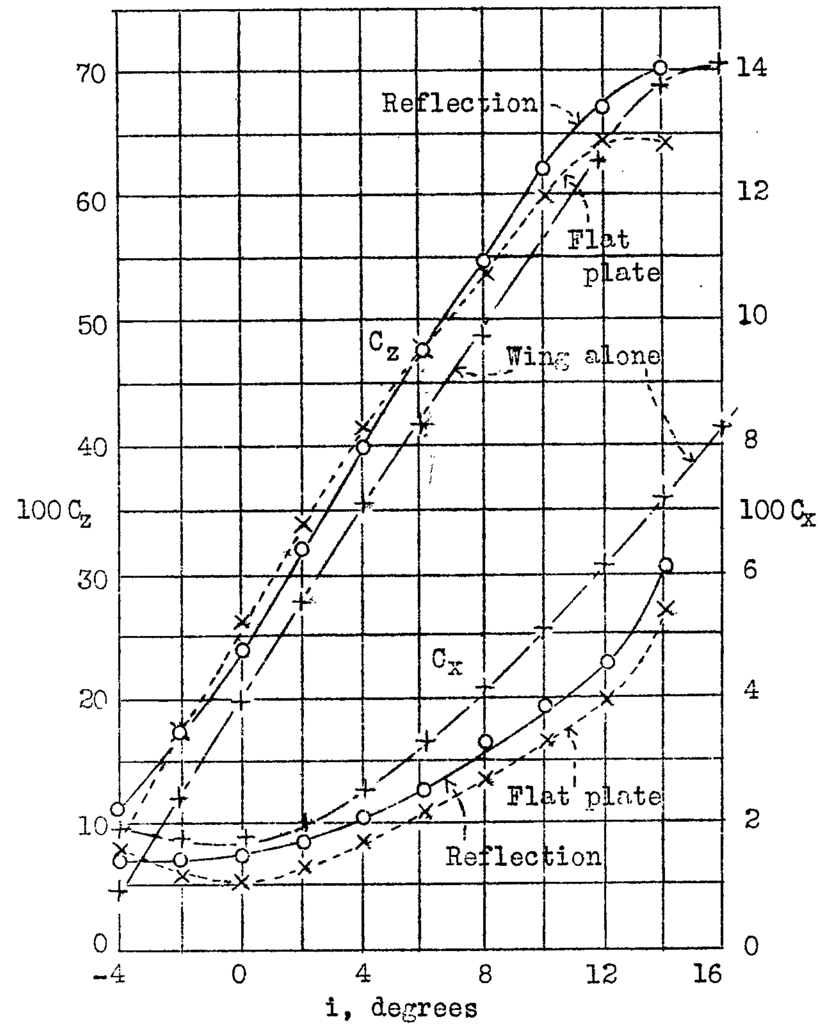


Figure 5.- Airfoil U.S.A. 27, ground at 1/2 chord, wind speed 48.27 km/hr.

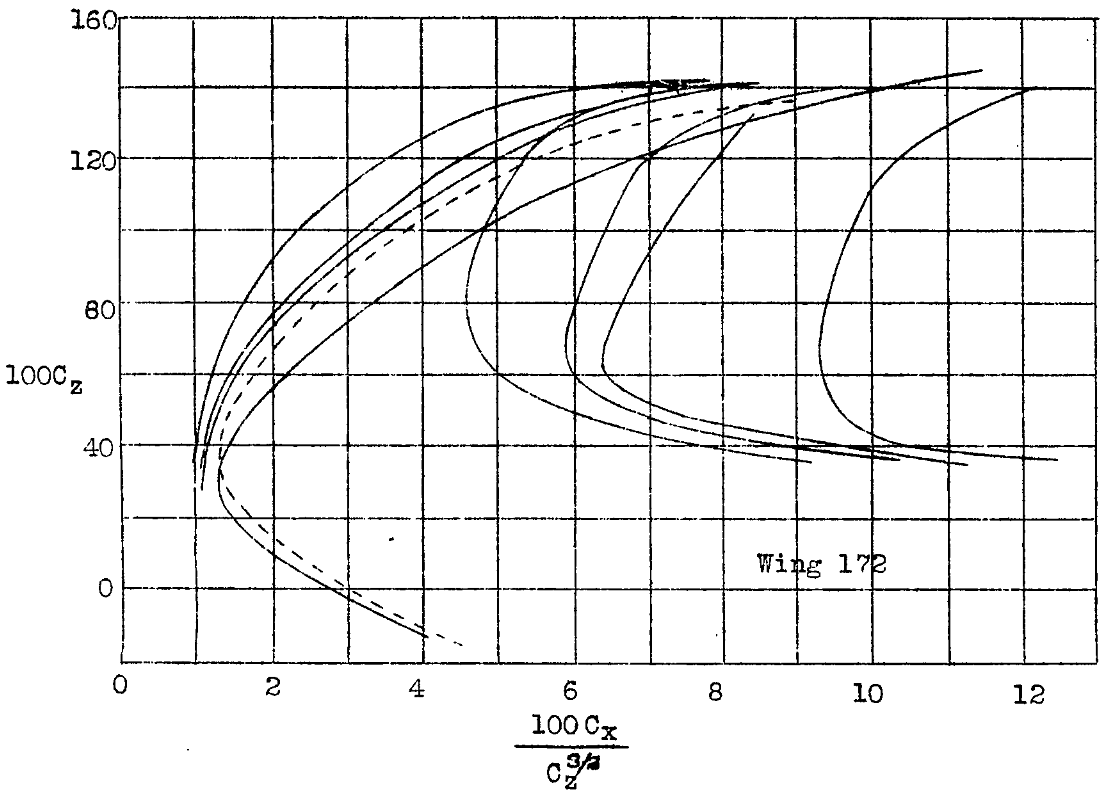


Figure 6.- The experimental σ values as measured by flat plate method are substantially twice the theoretical values of Prandtl - Wieselsberger.

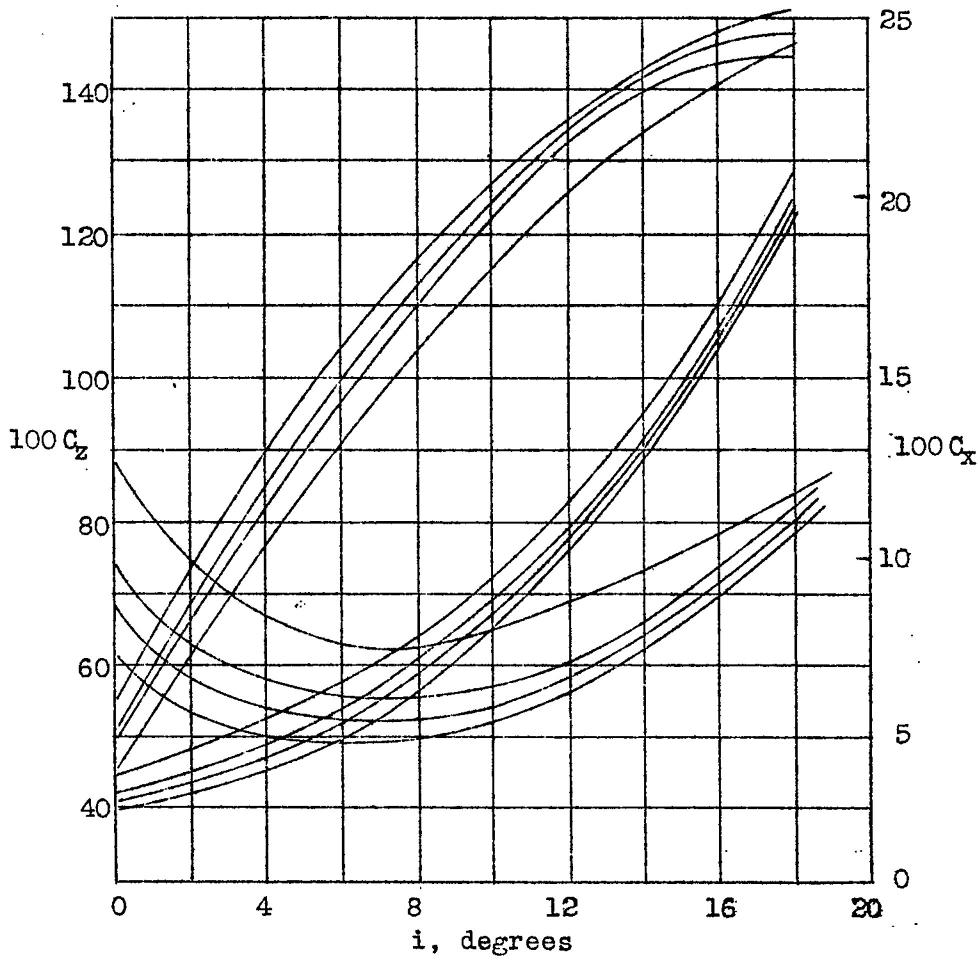


Figure 7.- Airplane 287, wing 215

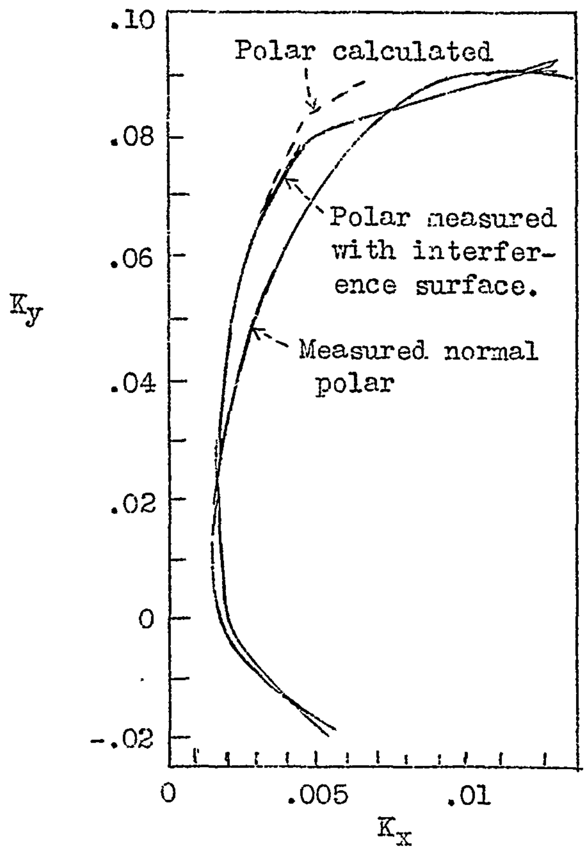


Figure 8.- Wieselsberger (reference 5)

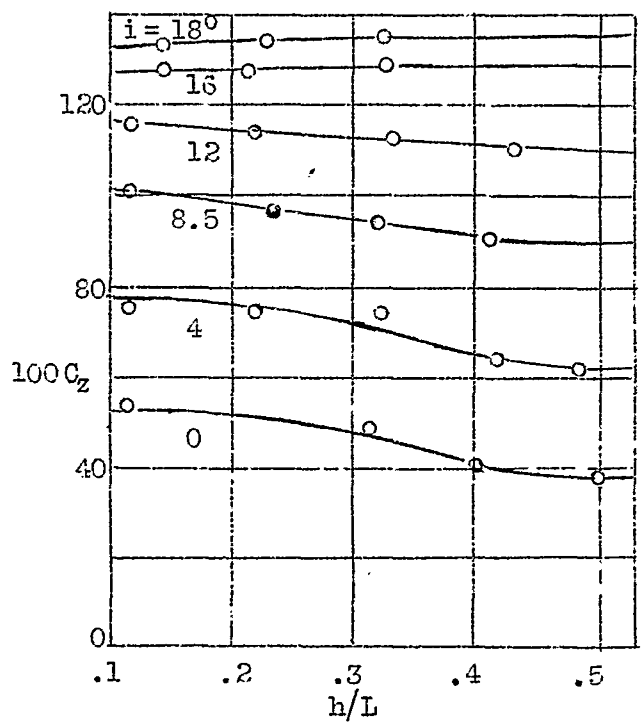


Figure 9.- Change of lift versus ground proximity for different angles of incidence.

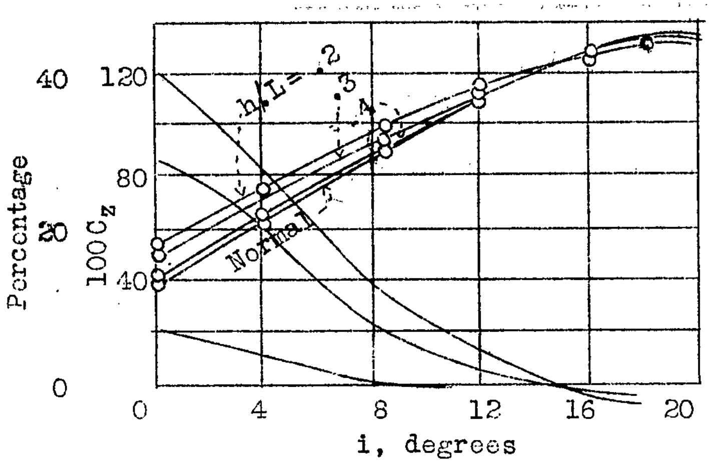


Figure 10.- Change of lift for different incidences and different ground distances, percentage lift increase to lift of wing alone.

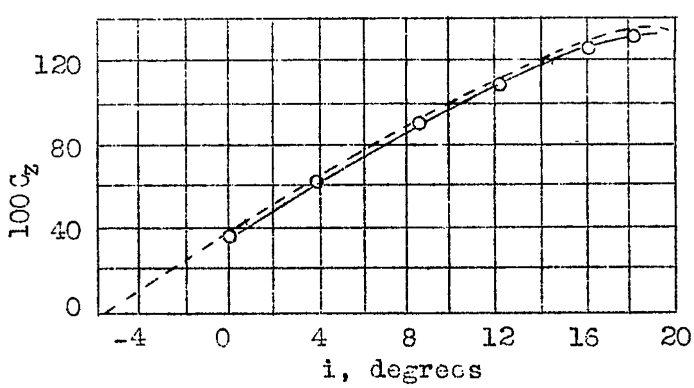


Figure 11.- Comparison of results for an identical airfoil on carriage and in Göttingen wind tunnel.

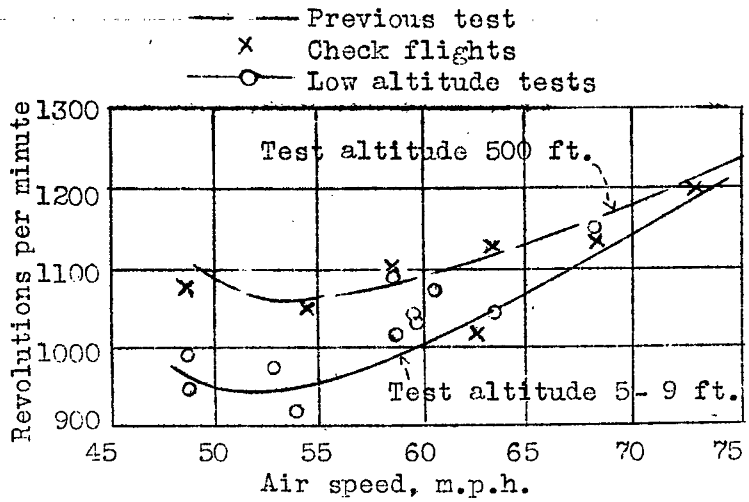


Figure 12.- The r.p.m. curve versus air speed for 500 feet altitude and for low altitude.

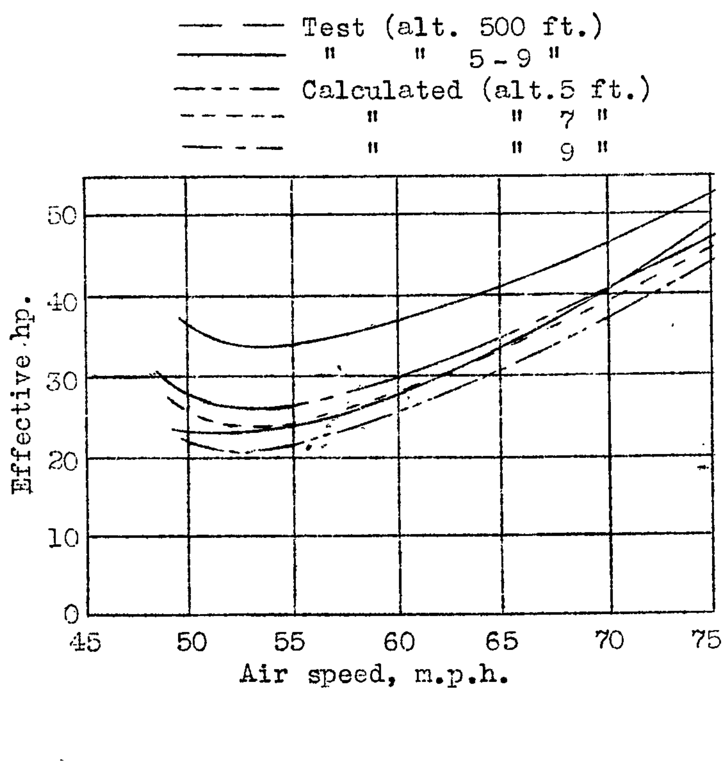
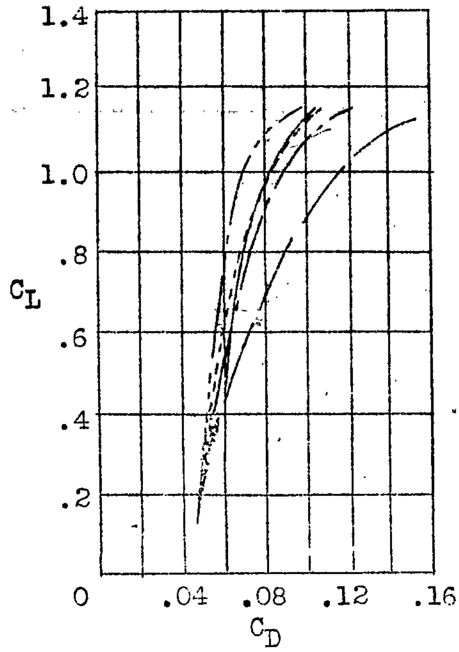


Figure 13.- Effective horsepower curves versus air speed.



Test (alt.500 ft.)
" " 5-9 "
Calculated (alt.5 ft.)
" " 7 "
" " 9 "

Figure 14.- Normal polar curve of VE -7 airplane as determined by glide tests.

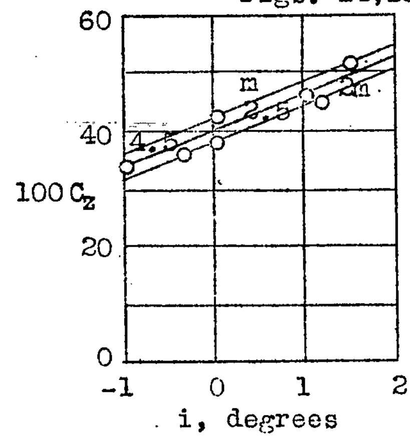


Figure 15.- Flight test. Lift change versus angle of incidence for different h.

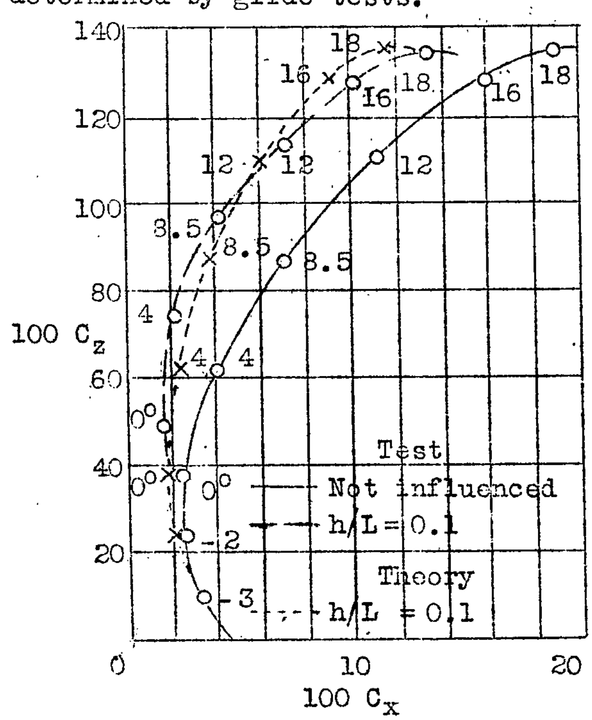


Figure 16.- Polar of model wing according to carriage tests.

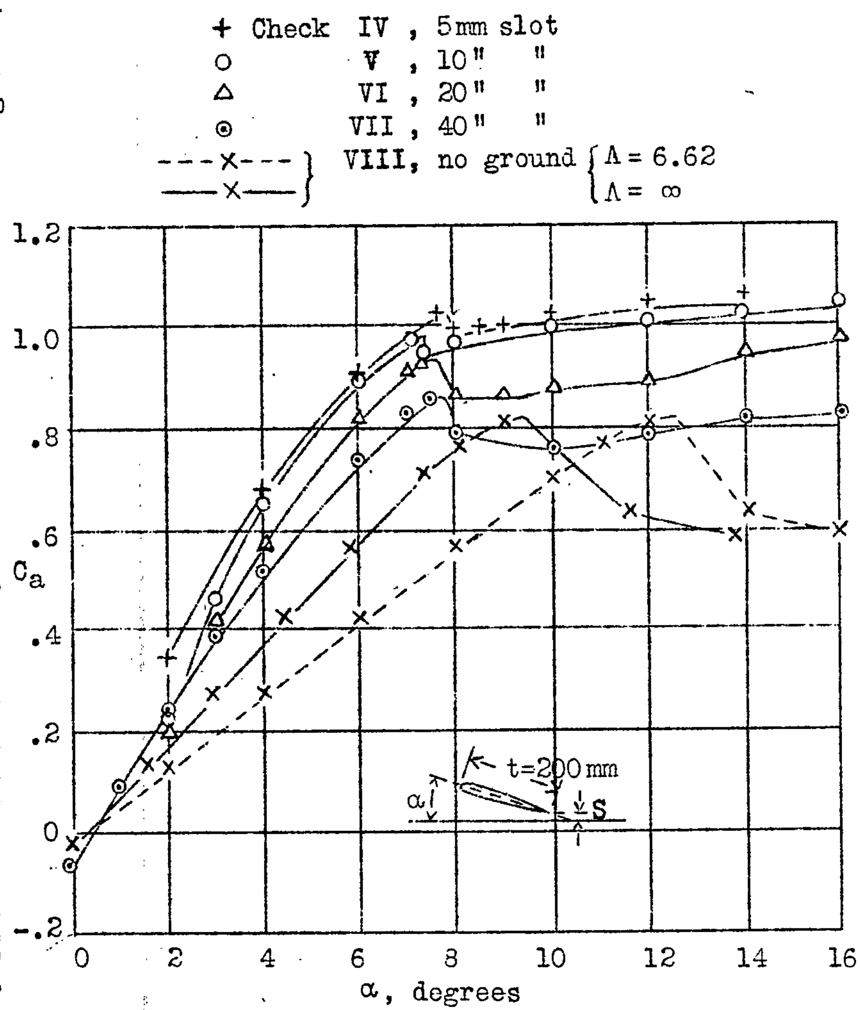


Figure 17.- Wing with end plates.

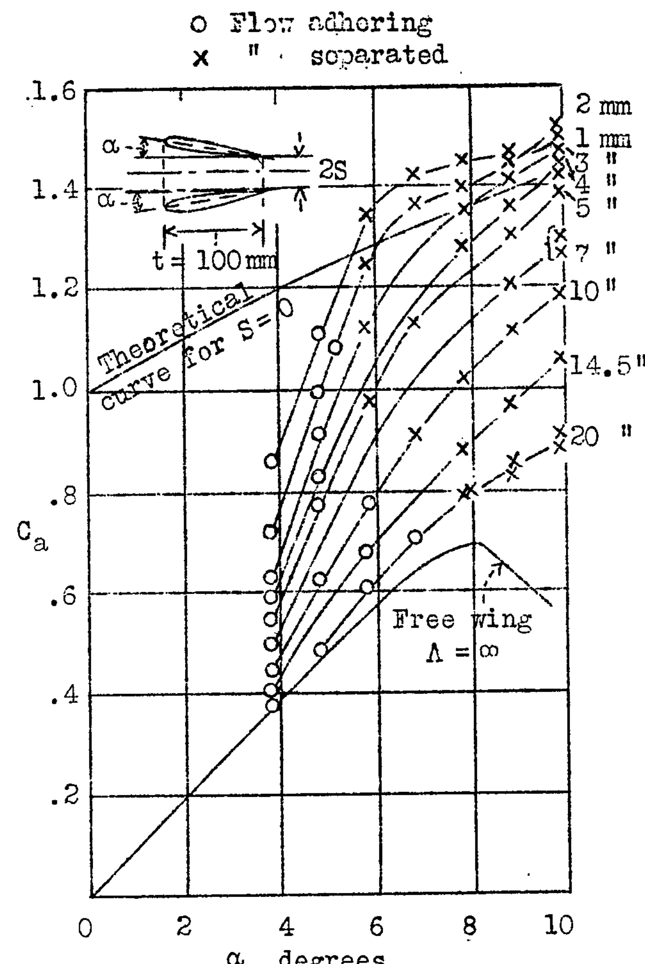


Figure 19.- Lift by reflection method.

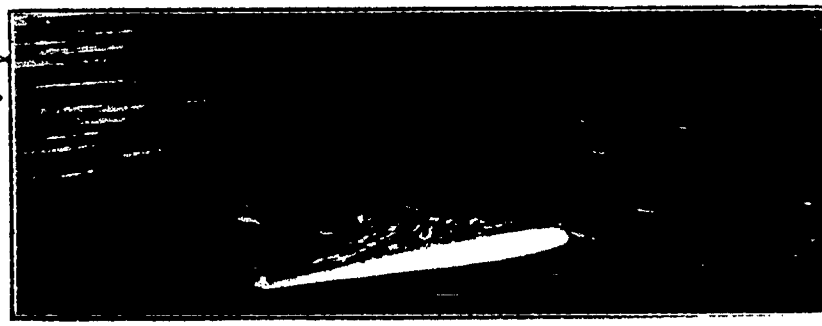


Figure 18.- Thickened boundary layer

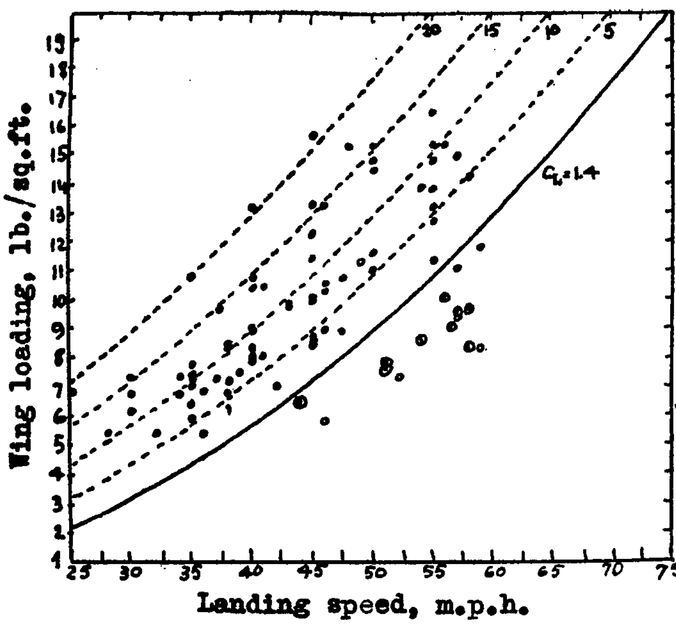


Figure 22.- Elliot G. Reid (reference 15)

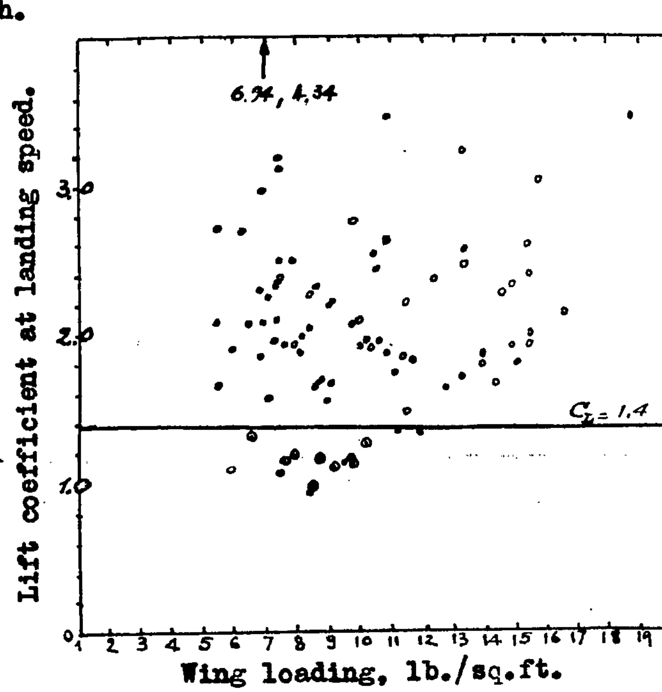


Figure 23.- Elliot G. Reid (reference 15)

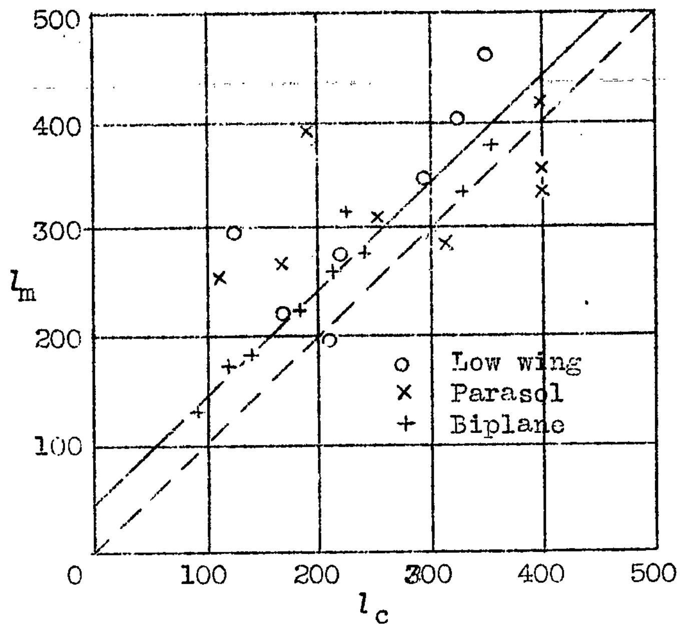


Figure 20.- Comparison of measured (l_m) and computed (l_c) rolling distance at take-off for different airplanes.

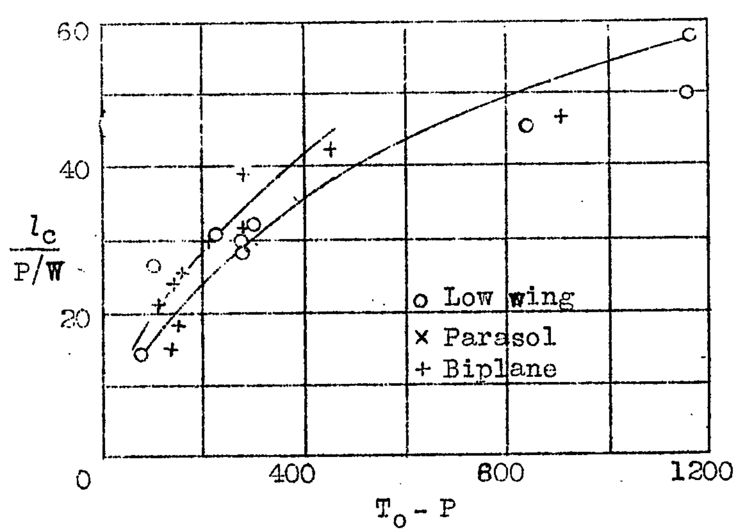


Figure 21.- Ratio of rolling at take-off to power loading versus thrust in kg.